OsteoArthritis and Cartilage (2007) **15,** 666–672

doi:10.1016/j.joca.2006.12.003

Osteoarthritis and Cartilage

ICRS International Cartilage Repair Society

OARSI OSTEOARTHRITIS RESEARCH SOCIETY INTERNATIONAL

Women have thinner cartilage and smaller joint surfaces than men after adjustment for body height and weight

I. G. Otterness Ph.D., Adjunct Professor†* and F. Eckstein M.D., Professor‡§
† *Division of Biomedical and Pharmaceutical Sciences, University of Rhode Island, Kingston, RI, USA*
‡ *Institute of Anatomy and Musculoskeletal Research, Paracelsus Medical University Salzburg, Strubergasse 21, A 5020 Salzburg, Austria*
§ *Chondrometrics GmbH, Ainring, Germany*

Summary

Objective: Females have a higher incidence of knee osteoarthritis (OA) than males, but the reason for this is unclear. Here we examine the hypothesis that women have smaller joint surfaces than men, independent of weight and height, and thus encounter higher articular pressures that might contribute to the higher incidence of OA in the female knee.

Methods: Forty healthy women and 57 men (21–39 years) with a body mass index of 16.8–32.8 were studied using magnetic resonance imaging. The right knee was scanned and proprietary software was used to determine the area of subchondral bone (cAB), mean cartilage thickness (ThC) and cartilage volume (VC) for all knee cartilage plates. Multilinear regression was used to correct the data for sex differences in height and weight.

Results: cAB, ThC, and VC were larger in men than in women in all knee cartilage plates. Correction for height and weight differences between the sexes reduced but did not eliminate sex differences in these parameters. The cAB was a strong predictor of VC independent of sex, height and weight, but did not predict ThC.

Conclusion: Men have greater knee cABs, ThC and VC than females even after correction for height and weight. Nonetheless, estimated tibial and patellar pressures are similar between sexes and thus are unlikely to account for the sex differences in OA incidence.

Key words: Knee cartilage volume, Knee cartilage area, Knee cartilage thickness, Sex differences in knee cartilage, MRI determination of knee cartilage morphology.

Introduction

It has been long recognized that there is a higher incidence of knee osteoarthritis (OA) in women compared to men[1–3]. A variety of potential explanations have been presented: These range from physical factors such as muscle weakness and malalignment[2], obesity[4,5], greater susceptibility to joint injury[6], hormonal factors including post menopausal remodeling of the cartilage[7] and a smaller cartilage volume (VC) compared with men[8]. The latter suggestion is based on parallel observations in bone, where a high peak bone mass in adolescence is known to be protective, and a low peak bone mass is known to increase the risk of osteoporosis[9].

Recently the first databases on normal (healthy) cartilage morphology have been published[10–12]. Several groups have analyzed sex differences of cartilage morphology, generally focusing on VC[8,13–16]. For example, Cicuttini *et al.*[8] measured the femoral, tibial and patellar VCs in 28 subjects and Ding *et al.*[17] in 374 subjects and they reported men to have larger VCs than women after multivariate corrections that included height, weight, body mass index (BMI) and femoral condylar volume. VC is determined by both the size of the bone cartilage interfacial (subchondral) area (cAB)/joint surface area and the cartilage thickness (ThC). Therefore when analyzing sex differences in VC, there is a confounding of both parameters. It remains unclear whether (and to what extent) sex differences are due to differences in ThC or subchondral bone/joint surface area or both. Cicuttini *et al.*[18] reported in 166 subjects that the mean medial and lateral tibia ThC measured by calipers was greater in men than women. Faber *et al.*[19] analyzed sex differences in ThC and subchondral bone/cartilage surface areas in a small sample of nine men and nine women and reported the sex differences in surface areas to be substantially larger than those in ThC.

To determine whether these sex differences in cartilage morphology represent "true" sex differences, or whether they simply result from the fact that men are on the average taller and heavier than women, we have carried out multivariate correction for height and weight and examined BMI and age as possible additional confounding variables. We also examined whether the cAB might serve as a good predictor of normal VC and thus possibly provide a value against which to estimate cartilage changes with age and disease. Finally, having the body weight and surface area, we examine the possibility that higher pressures (weight/joint surface area) acting in the knee

*Address correspondence and reprint requests to: Dr Ivan Otterness, Ph.D., 241 Monument St. #5, Groton, CT 06340, USA. Tel: 1-860-460-0553; E-mail: IGO@otterness.net
Received 1 June 2006; revision accepted 3 December 2006.

might be a contributor to the higher incidence of OA in the female knee.

Subjects and methods

SUBJECTS AND KNEES

We examined the right knees of 97 healthy volunteers without symptoms or signs of musculoskeletal disease, no history of pain, trauma or operations of the knee, and no history of fracture or immobilization. Subjects with obvious cartilage lesions on the magnetic resonance imaging (MRI) scans were excluded from the study. Each subject was characterized by sex, height, weight, and BMI. Of the 97 individuals 40 were females (age 20–38 years; mean 25.5 ± 4.6) with a height range of 156–184 cm and a weight range of 48–86 kg. Fifty-seven subjects were males (age 21–37 years; mean 25.5 ± 3.3) with a height range of 155–196 cm and a weight range of 60–108 kg. There was no significant difference in age between the men and women. Three subjects (one woman, two men) were underweight (BMI < 18.5), 75 (38 women, 37 men) were considered normal weight ($18.5 \leq$ BMI < 25), 17 (17 men, no woman) were considered overweight ($25 \leq$ BMI < 30) and two (one woman, one man) were considered obese (BMI ≥ 30). Written information was first given to potential participants explaining the nature of the examination and the specific goals of the study. Afterward, written consent was obtained from those who volunteered. The study protocol and the informed written consent documents were ratified by the local ethics committee.

MRI METHOD AND COMPUTATION OF CARTILAGE MORPHOLOGY

All individuals were asked to physically rest for 1 h prior to imaging to avoid load-induced compression of the cartilage[20]. MRI was performed at the right knee joint with a 1.5 T magnet (Magnetom Vision, Siemens, Erlangen, Germany), a circumferentially polarized extremity coil, and a previously validated water excitation fast low angle shot (FLASH) gradient echo sequence[21–24] [repetition time (TR) = 17.2 ms, echo time (TE) = 6.6 ms, flip angle (FA) = 20°]. Sagittal images were obtained at a section thickness of 1.5 mm and an in-plane resolution of 0.31 mm × 0.31 mm [field of view (FOV) = 16 cm, 512 × 512 pixel matrix] at an acquisition time of 9 min 15 s.

All data sets were transferred digitally to a workstation (Octane Duo, Silicon Graphics, Mountain View, CA) with a high-performance graphic system. Segmentation of the patellar (P), medial tibial (MT), lateral tibial (LT), and femoral (F) cartilage was performed interactively on a section by section basis with a B-spline Snake (deformable contour) algorithm[22,25,26]. The femoral region of interest was divided interactively into the trochlear (TrF) and the medial (MF) and lateral (LF) femoral condyles by projecting the intercondylar notch from a central slice laterally. The VC and mean cartilage thickness (ThC.Me) were computed as described previously[27]. Also the subchondral bone area (cAB = cartilage covered area of subchondral bone) and the cartilage surface area (AC) were computed using previously validated methodology[28]. Note that all subjects had healthy cartilage and no denuded areas so that the cAB always corresponded with the total area of subchondral bone (tAB). Also note that AC correlated very highly with cAB ($r^2 = 0.99$) in this sample for the total knee so that throughout the paper only cAB will be used, because analysis of AC produces identical results. Quantitative data for the entire knee joint (K) were derived by adding up the volumes and surfaces of the individual cartilage plates. The ThC.Me was derived by adding up the mean values of all cartilage plates, and by weighting them in proportion to the cAB of each plate[22,29].

STATISTICAL ANALYSIS

Data analysis was carried out in Mathematica (Wolfram Research, Champaign, IL) using the Statistics modules ConfidenceIntervals and MultiLinearRegression. To correct for confounding variables, multilinear regression with stepwise elimination of nonsignificant variables was performed to find significant relationships between the variables height, weight, BMI, age and sex with parameters of cartilage morphology. In short, multilinear regression was initially carried out with all five variables included in the model. The least significant variable was removed and the multilinear regression recomputed. This process of variable elimination was continued until only significant variables ($P < 0.05$) remained in the model. Regression analyses in which weight was a variable were performed both on the entire sample population and on the population that was restricted to the 75 normal weight individuals (38 women, 37 men).

The force on the knee when standing on both legs was simplistically estimated as body weight in Newtons divided by the total cAB of the right and left tibial plateaus. Since only a portion of cAB will make up the contact area, it was termed a relative pressure. Given the high symmetry between the left and right knee observed previously[30], the relative pressure acting on the cartilage was estimated as

$$\frac{\text{body weight}}{2} \times (\text{MT.cAB} + \text{LT.cAB}) \tag{1}$$

A similar calculation was made for the patella. While a variable portion of the body weight will be transmitted through the patella depending on the knee angle, we presumed that the forces will be proportional to body weight and that a relative pressure can be estimated as body weight divided by the total cAB of the right and left patellae. Thus for each individual, the relative pressure was estimated as

$$\frac{\text{body weight}}{2} \times \text{P.cAB} \tag{2}$$

Results

SEX DIFFERENCES IN CARTILAGE MORPHOLOGY

For the knee, males had an average of 102 ± 9 cm^2 of cAB vs 79 ± 7 cm^2 in females (Table I), the difference being 23 cm^2 or 29%. In all six knee cartilage plates, cAB was significantly larger in males than females ($P < 0.001$), the difference ranging from 24% (MF) to 32% (MT). Comparing plates, MT.cAB was similar to LT.cAB in both males and females, but MF.cAB was larger than LF.cAB. The difference was sex dependent with the ratio (MF/LF) being 1.20 in females and 1.13 in males ($P = 0.02$).

For the knee, cartilage in males (2.14 ± 0.24 mm) was significantly thicker than in females (1.76 ± 0.21 mm, Table II), the difference (0.38 mm or 22%) being highly significant ($P < 0.001$). This finding applied to most cartilage

Table I
Subchondral bone area (cAB) of the knee cartilage plates: sex differences

Cartilage plate	cAB (cm^2)		Sex difference uncorrected (cm^2)*	Sex difference height corrected†	Sex difference weight corrected
	Male	Female			
MT	13.0 ± 1.8	9.9 ± 1.4	3.16	2.42	2.04
LT	12.9 ± 1.7	9.9 ± 1.4	2.95	1.53	1.21
MF	21.2 ± 3.0	17.1 ± 2.5	4.15	1.86	1.16
LF	18.9 ± 2.4	14.3 ± 1.7	4.67	2.45	2.21
P	13.7 ± 1.8	10.8 ± 1.3	2.94	1.50	1.22
Tr	22.7 ± 2.6	17.8 ± 2.3	4.93	3.40	4.07
K	102 ± 9.1	79.2 ± 7.4	22.9	13.5	12.3

Abbreviations: Medial tibial (MT), lateral tibial (LT), medial femoral condyle (MF), lateral femoral condyle (LF), trochlea (Tr), patella (P) and knee (K).

*All uncorrected differences were $P < 0.001$.

†The multilinear regression $cAB = A + B \times sex + C \times$ height or weight was used to correct the sex difference in area for height or weight. A is a constant, B is the additional area in males (male = 1, females = 0) independent of height or weight, C gives the linear dependency on either height ($N = 97$) or weight ($N = 75$) independent of sex. If both height and weight were entered into the regression together, weight lost its significance. BMI and age were uncorrelated with cAB. All corrected differences were $P < 0.01$.

plates (Table II) with the difference in thickness ranging from 17% (LT) to 32% (MF). The patella was an exception, the ThC difference was minor (6%) and barely reached significance ($P = 0.03$). In both sexes, the lateral plates were thicker than the medial plates (LT > MT and LF > MF), and the tibial plates were thicker than the femoral plates (MT > MF and LT > LF). There was a significant difference between the sexes in the ratio of the thickness of the tibia vs femoral condyle, both medially (MT/MF = 1.26 for women vs 1.14 for men, $P = 0.02$) and laterally (LT/LF = 1.26 for women vs 1.16 for men, $P = 0.003$).

For the knee VC, males had an average of 27.0 ± 4.5 ml and females 17.7 ± 2.7 ml. The difference was 9.3 ml or 52% (Table III). LT.VC was larger than MT.VC in males and females, with no sex difference in the ratio. MF.VC was larger than LF.VC, and the MF/LF ratio was significantly greater ($P = 0.001$) in females (1.20) than in males (1.08). Similarly, MF.VC was significantly larger than MT.VC, but there was no difference between the sexes. LF.VC was also larger than LT.VC in both males and females and the ratio LF.VC/LT.VC was significantly greater in males (1.36) than in females (1.21, $P < 0.001$).

SEX DIFFERENCES IN CARTILAGE MORPHOLOGY AFTER CORRECTION FOR CONFOUNDING VARIABLES

No significant correlation of cAB, ThC.Me, and VC was found with either BMI or age in any knee cartilage plate when used in a multilinear regression that included height, weight and sex. Therefore age and BMI were eliminated in the first steps of the stepwise elimination process. Height and weight were significant confounding variables for nearly all cartilage parameters in all cartilage plates, and are related to each other. The males averaged 18 kg heavier than females, and when corrected for the height difference between males and females, the differences was 11 kg. When a normal weight population was used (eliminating 17 overweight, two underweight and one obese men, and one underweight and one obese women), males were on average 6.6 kg heavier than females at any given height (Fig. 1).

Table II
Mean cartilage thickness (ThC.Me) of the knee cartilage plates: sex differences

Cartilage plate	Cartilage thickness (mm)			Sex difference corrected weight†
	Male	Female	Sex difference*	
MT	1.88 ± 0.26	1.57 ± 0.25	0.31	0.22
LT	2.33 ± 0.33	1.98 ± 0.26	0.35	0.15
MF	1.71 ± 0.35	1.29 ± 0.28	0.42	0.20
LF	2.02 ± 0.29	1.58 ± 0.22	0.44	0.32
P	2.82 ± 0.42	2.65 ± 0.44	0.17	-0.10^{ns}
Tr	2.27 ± 0.32	1.77 ± 0.26	0.49	0.31
K	2.14 ± 0.24	1.76 ± 0.21	0.38	0.19

Abbreviations as in Table I.

*All uncorrected sex differences ($P < 0.001$) except the patella where $P = 0.03$.

†The regression $ThC.Me = A + B \times sex + C \times weight$ was used to correct differences in thickness for differences in body weight ($N = 75$). All corrections were significant ($P < 0.01$) except for the patella (ns = not significant). Height was not a significant regressor against ThC.Me, so there is no height correction.

Table III
Cartilage volume (VC) of the knee cartilage plates: sex differences

Cartilage plate	VC (ml)		Sex difference (ml)	Sex difference height corrected*	Sex difference weight corrected†
	Male	Female			
MT	2.99 ± 0.63	1.93 ± 0.36	1.05	0.92	0.66
LT	3.53 ± 0.77	2.37 ± 0.40	1.16	0.71	0.47
MF	5.12 ± 1.16	3.41 ± 0.58	1.70	1.26	0.75
LF	4.75 ± 0.99	2.87 ± 0.54	1.88	1.28	0.99
P	4.45 ± 0.88	3.32 ± 0.68	1.13	0.59	0.26
Tr	6.16 ± 1.00	3.82 ± 0.75	2.34	1.95	1.62
K	27.0 ± 4.5	17.7 ± 2.7	9.27	6.71	4.73

Abbreviations as in Table I.

*All uncorrected sex differences, $P < 0.001$.

†The multilinear regression $CV = A + B \times sex + C \times$ height or weight was used to correct the sex difference in volume for height or weight. A is a constant, B is the additional volume (ml) in males (male = 1, females = 0) independent of height or weight, C is the linear dependency on height ($N = 97$) or weight ($N = 75$) independent of sex. BMI and age were uncorrelated with volume of cartilage.

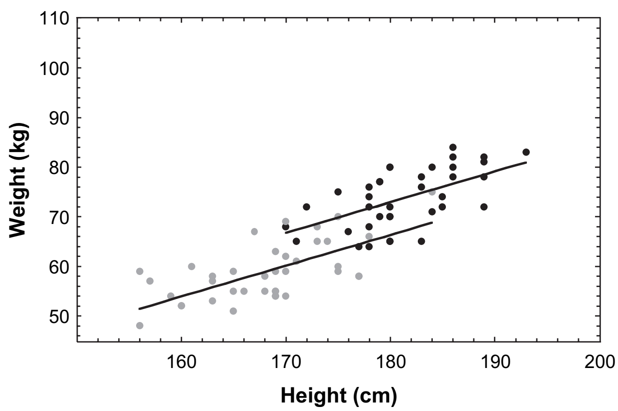

Fig. 1. Correlation of weight in the normal population with height and sex. Multilinear least squares regression is used to fit the equation cAB $= -32.0 + 11.3 \times$ sex $+ 0.544 \times$ height using the normal weight population ($r^2 = 0.57$, $P < 0.001$, $N = 75$). A 5.6 kg difference is seen between males and females at any given height. In the regression, sex = 1 for males and sex = 0 for females. Males (●) and females (●).

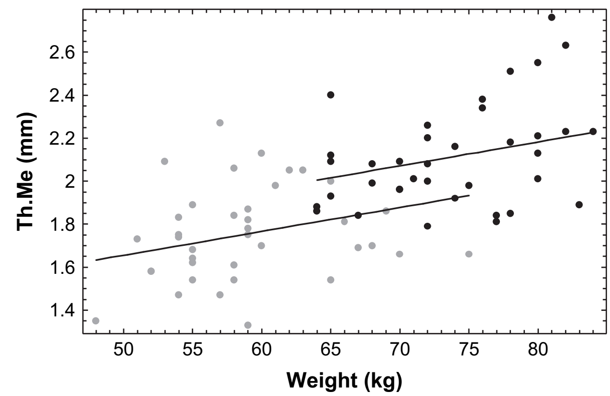

Fig. 3. Correlation of the mean cartilage thickness (ThC.Me) in the knee with weight where the regression lines are fit to the equation ThC.Me $= 1.10 + 0.194 \times$ sex $+ 0.0111 \times$ weight using the normal weight population ($r^2 = 0.043$, $P < 0.001$, $N = 75$). In the regression, sex = 1 for males and sex = 0 for females. Males (●) and females (●).

Multilinear regression demonstrated that a significant part of the difference in cAB between the sexes was accounted for by the difference in height. For the knee, sex and height were highly correlated with cAB ($r^2 = 0.76$; $P \ll 0.001$). Controlling for the height difference between males and females [Fig. 2(a)], it was estimated that a male has approximately a 13.5 cm^2 larger cAB than a female whereas without correction the difference was 22.9 cm^2. The differences in the cartilage plates ranged from 11% (MF) to 25% (MT) larger cAB in males, after adjusting for height differences. For the knee, sex and weight were highly correlated with cAB [$r^2 = 0.77$; $P \ll 0.001$, Fig. 2(b)]. The difference in cAB between the sexes was 12.3 cm^2 for individuals after adjustment for weight (Table I).

Height did not significantly correlate with ThC.Me when sex was a variate ($P = 0.38$) while weight provided a small ($r^2 = 0.43$ vs $r^2 = 0.40$), but significant ($P = 0.01$) additional contribution when normal weight individuals were used. For the knee, correction for weight reduced sex difference in ThC.Me from 0.38 to 0.19 mm (Fig. 3); however, men still displayed thicker cartilage in the knee and in each plate than women after adjusting for weight (Table II).

Sex, weight and height were correlated with VC of the knee ($r^2 = 0.68$; $P < 0.001$). Either height or weight could be dropped with little effect on the correlation ($r^2 = 0.65$ after dropping height or $r^2 = 0.64$ after dropping weight), but not both. Fig. 4(a) shows the correlation of VC with height for the knee and Fig. 4(b) that for VC and weight. In each cartilage plate, correction for height or weight reduced VC differences between men and women, but correction for weight reduced VC differences more extensively (Table III). For the knee, the sex difference was reduced from 9.3 to 6.7 ml with height correction and to 4.7 ml after weight correction. However, neither correction for height nor weight eliminated the volume differences between the sexes for any plate.

RELATIONSHIP OF cAB to ThC.Me AND VC

There was a very high correlation of cAB with VC for all cartilage plates (Table IV). cAB alone accounted for the vast majority of the variance in VC (85% for the knee, Fig. 5) and alone better accounted for the variance than sex, height and weight together. This was not true for thickness; the combination of height, weight and sex was in all cases better than the regression with cAB alone. Adding

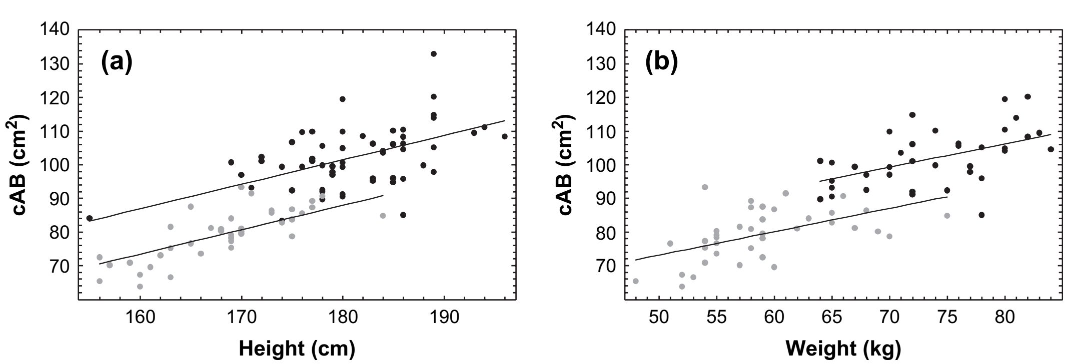

Fig. 2. Correlation of the subchondral bone area (cAB) in the knee with (a) height where the regression lines are fit to the equation cAB $= -42.9 + 13.5 \times$ sex $+ 0.727 \times$ height ($r^2 = 0.76$, $P < 0.001$, $N = 97$) and (b) weight where the regression lines are fitted by the equation cAB $= 55.7 + 15.6 \times$ sex $+ 0.395 \times$ weight ($r^2 = 0.71$, $P < 0.001$, $N = 75$) using the normal weight population. In both regressions, sex = 1 for males and sex = 0 for females. Males (●) and females (●).

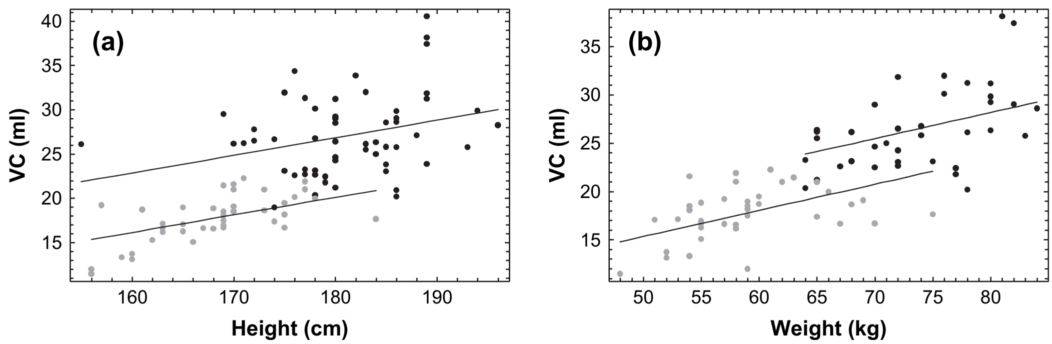

Fig. 4. Correlation of the volume of cartilage (VC) in the knee with (a) height where the regression lines are fit to the equation VC = −15.6 + 6.72 × sex + 0.198 × height ($r^2 = 0.67$, $P < 0.001$, $N = 97$) and (b) weight where the regression lines are fitted by the equation VC = 7.75 + 6.20 × sex + 0.168 × weight ($r^2 = 0.065$, $P < 0.001$, $N = 75$) using the normal weight population. In both regressions, sex = 1 for males and sex = 0 for females. Males (●) and females (●).

cAB to the regression of height, weight and sex did not improve the correlation with thickness.

ESTIMATED CARTILAGE PRESSURE BY SEX

The mean relative tibial pressure estimated in women was 0.143 ± 0.026 MPa and in men 0.142 ± 0.022 MPa when analyzing the entire sample, and 0.141 ± 0.017 MPa in women and 0.135 ± 0.017 MPa in men when only looking at normal weight subjects (Fig. 6). The pressures were not significantly different ($P > 0.05$) between men and women in the entire and in the normal weight group.

The mean relative patellar pressure was 0.546 ± 0.084 MPa in women and 0.558 ± 0.075 MPa in men and, when considering only normal weight subjects, was 0.541 ± 0.069 MPa in women and 0.542 ± 0.053 MPa in men [Fig. 6(b)]. Again, the pressures were not significantly different in the entire or the normal weight group.

Discussion

In all cartilage plates of the knee, males are observed to display a larger subchondral bone/cartilage surface area, thicker cartilage and greater VC than females. This raises the question whether the smaller area of the subchondral bone/cartilage surface or the thinner cartilage could be a contributing factor or even the cause of the higher incidence of OA in women.

Men are on the average taller and heavier than women and it is possible that this difference accounts for the differences in cartilage area, thickness and volume. Controlling for height was straightforward, since height is largely fixed in a young cohort once growth is complete. However, controlling for weight was more involved because weight was very variable in the sample with individuals varying from underweight to obese. To minimize the effects of this variation, the analysis was repeated using only individuals of normal weight when weight was a primary variable. This reduced the size of the data set from 97 to 75 individuals, eliminated bias in the distribution of overweight individuals (more men than women) in our data set, and increased the correlations with height and weight with cAB, ThC.Me and VC.

The cAB showed a substantial and significant sex difference. A part of that difference could be attributed to height and weight differences, with weight accounting for slightly more of the sex difference than height. Nevertheless, the

Table IV
Correlation of the cartilage volume (VC) with the subchondral bone area (cAB)

Cartilage plate	Regression against cAB only (r^2)*	Regression against height, weight, sex (r^2)†
MT	0.81	0.49
LT	0.77	0.53
MF	0.70	0.51
LF	0.77	0.65
P	0.71	0.46
Tr	0.67	0.64
K	0.84	0.66

Abbreviations as in Table I.

*The regression VC = intercept + slope × cAB was fitted for all 97 subjects for each cartilage plate. r^2 gives the fraction of the variance accounted for by the regression. The regression on cAB removes all the sex, height and weight dependency of VC.

†r^2 is the fraction of variance accounted for by the regression VC = $a + b$ × cAB or the regression VC = $A + B$ × sex + C × height + D × weight. In all cases, $P < 0.001$.

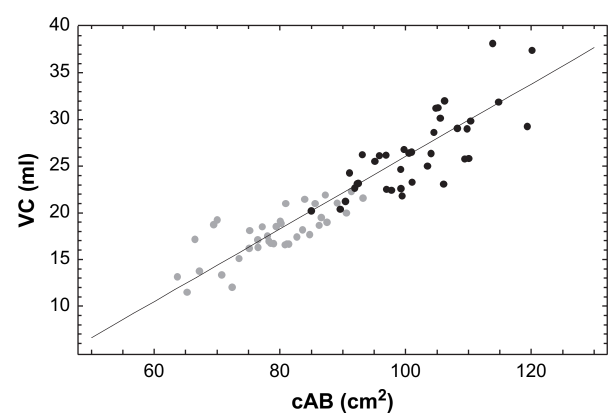

Fig. 5. Correlation of subchondral bone area (cAB) with the cartilage volume (VC) of the knee. A multilinear regression of VC with cAB, height, sex, weight, BMI and age was carried out. After stepwise elimination of nonsignificant variables, the only remaining significant relationship was with cAB. The best fit line VC = −12.8 + 0.389 × cAB is shown with the individual values ($r^2 = 0.84$, $P < 0.001$, $N = 97$).

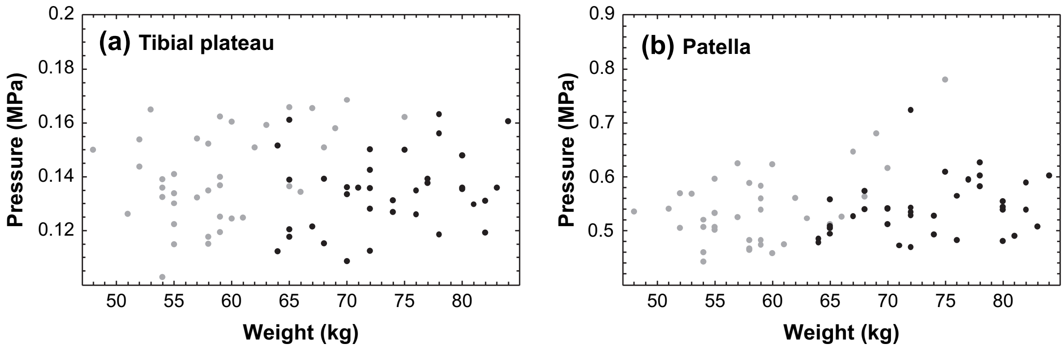

Fig. 6. Relationship between the computed static pressures on the tibial plateau and on the patella if the entire body weight were transmitted through the subchondral bone area (cAB) of (a) the right and left tibial plateaus and (b) the right and left patellas. The computed pressure for each individual is plotted at the individuals' body weight. Males (●) and females (●). Only normal weight individuals are shown ($N = 75$). The pressure difference between males and females is not significant ($P > 0.05$) for the tibia or for the patella.

sex difference in cAB remained highly significant even after correction for height or weight. To understand the implications of the sex difference in cAB, the relative pressures acting on the tibial plateau and on the patella were estimated. In both cases, body weight was used as a surrogate for the actual applied load because it is well recognized that the joint forces scale with body weight[31], even if it is clear that a main contributor to the joint loads are the muscle forces that balance the moments created by body weight. It is also well known that the forces are distributed over only a portion of the surface. Assuming that these proportions are comparable in men and women, the pressures on the tibia computed as body weight/cAB were not significantly different between men and women. The pressures on the patella were also not significantly different.

For cAB, males and females can be reasonably fit by a univariate linear regression, e.g., for the tibial cAB, sex alone ($r^2 = 0.53$) and weight alone ($r^2 = 0.57$). The strength of the weight alone regression makes the lack of significant sex difference in pressure reasonable. It also indicates that the weight differences account for more of the actual variance than the sex differences when the ratio of weight to cAB is taken. Thus from the perspective of static loading, the cAB appears to be scaled to the normal weight differences between the sexes. This is consistent with the work of Simon[32] who found that static compressive loading of joints was similar even across species that differed by as much as 12,000$\times$ in weight. The weight difference between the sexes is only 25%. Since loading is similar, this difference should not contribute to the sex difference in OA incidence.

In multivariate analysis, age was not an important factor. Our sample was young and had a narrow age range. Age appears to become an important parameter only in the over 50 age group[17]. BMI was also not an important factor in determining VC. As a univariate parameter it is significant[8], but entering weight and/or height removed its significance. Nonetheless, joint pressures increase directly with BMI and thus BMI is more directly related to disease than anatomical parameters. Anderson and Felson[33] showed that in both males and females the incidence of knee OA increases with BMI. Jarvhom *et al.*[34] (studying only males) showed that the incidence of severe OA increases with BMI even within the low and normal weight range.

Cartilage was thicker in males than females even after correction for height and/or weight. There is little evidence that thicker cartilage has better load bearing capacity than thin cartilage[20,35]. The ankle has thinner cartilage and a lower incidence of OA than the knee[36] and bovine, for example, have thinner knee cartilage than men[32] yet carry far heavier loads. However, it has been suggested that thicker cartilage could provide some additional protection against shear stress[37].

VC is also larger in males than females. Correction for height or body weight also diminishes, but does not eliminate the difference in volume between sexes. Examination of the relationship of the cAB to volume showed that sex differences in cAB account for the sex differences in VC, as suggested by Faber *et al.*[19] from a smaller data set. In addition, cAB accounts for not only the sex but the height and weight dependence. Cicuttini *et al.*[13,17] have used normalization to the volume of the distal femur to enable estimation of changes that take place in VC with age and OA. Our data would suggest that the cAB of the cartilage plate could be used to estimate the normal VC. Interestingly, unlike VC, cAB was not a useful correlate with ThC. This indicates that additional factors play a role in determining ThC.Me.

In conclusions, men are found to have larger subchondral bone/joint surface areas, ThC, and VC than females in all knee cartilage plates, even after correction for height and weight. Nonetheless, tibial and patellar pressures were similar in both sexes. A very strong correlation was found for VC with cAB. This suggests that cAB might be useful to estimate normal VC.

References

1. Felson DT, Chaisson CE. Understanding the relationship between body weight and osteoarthritis. Baillieres Clin Rheumatol 1997;11:671−81.
2. Issa SN, Sharma L. Epidemiology of osteoarthritis: an update. Curr Rheumatol Rep 2006;8:7−15.
3. Srikanth VK, Fryer JL, Zhai G, Winzenberg TM, Hosmer D, Jones G. A meta-analysis of sex differences prevalence, incidence and severity of osteoarthritis. Osteoarthritis Cartilage 2005;13:769−81.
4. Felson DT. Relation of obesity and of vocational and avocational risk factors to osteoarthritis. J Rheumatol 2005;32:1133−5.
5. Holmberg S, Thelin A, Thelin N. Knee osteoarthritis and body mass index: a population-based case−control study. Scand J Rheumatol 2005;34:59−64.

6. Dugan SA. Sports-related knee injuries in female athletes: what gives? Am J Phys Med Rehabil 2005; 84:122–30.
7. Hanna FS, Wluka AE, Bell RJ, Davis SR, Cicuttini FM. Osteoarthritis and the postmenopausal woman: epidemiological, magnetic resonance imaging, and radiological findings. Semin Arthritis Rheum 2004;34:631–6.
8. Cicuttini F, Forbes A, Morris K, Darling S, Bailey M, Stuckey S. Gender differences in knee cartilage volume as measured by magnetic resonance imaging. Osteoarthritis Cartilage 1999;7:265–71.
9. Heaney RP, Abrams S, Dawson-Hughes B, Looker A, Marcus R, Matkovic V, *et al*. Peak bone mass. Osteoporos Int 2000;11:985–1009.
10. Cicuttini FM, Wluka A, Bailey M, O'Sullivan R, Poon C, Yeung S, *et al*. Factors affecting knee cartilage volume in healthy men. Rheumatology (Oxford) 2003;42: 258–62.
11. Hudelmaier M, Glaser C, Englmeier KH, Reiser M, Putz R, Eckstein F. Correlation of knee-joint cartilage morphology with muscle cross-sectional areas vs anthropometric variables. Anat Rec A Discov Mol Cell Evol Biol 2003;270:175–84.
12. Hudelmaier M, Glaser C, Hohe J, Englmeier KH, Reiser M, Putz R, *et al*. Age-related changes in the morphology and deformational behavior of knee joint cartilage. Arthritis Rheum 2001;44:2556–61.
13. Cicuttini FM, Wluka AE, Forbes A, Wolfe R. Comparison of tibial cartilage volume and radiologic grade of the tibiofemoral joint. Arthritis Rheum 2003;48:682–8.
14. Cova M, Frezza F, Shariat-Razavi I, Ukmar M, Mucelli RS, Dalla Palma L. Magnetic resonance assessment of knee joint hyaline cartilage according to age, sex, and body weight. Radiol Med (Torino) 1996;92:171–9.
15. Ding C, Cicuttini F, Scott F, Glisson M, Jones G. Sex differences in knee cartilage volume in adults: role of body and bone size, age and physical activity. Rheumatology (Oxford) 2003;42:1317–23.
16. Jones G, Glisson M, Hynes K, Cicuttini F. Sex and site differences in cartilage development: a possible explanation for variations in knee osteoarthritis in later life. Arthritis Rheum 2000;43:2543–9.
17. Ding C, Cicuttini F, Scott F, Cooley H, Jones G. Association between age and knee structural change: a cross sectional MRI based study. Ann Rheum Dis 2005;64:549–55.
18. Cicuttini F, Wluka A, Wang Y, Hankin J, Ebeling P. Compartmental diffferences in knee cartilage volume in healthy adults. J Rheumatol 2002;29:554–6.
19. Faber SC, Eckstein F, Lukasz S, Muhlbauer R, Hohe J, Englmeier KH, *et al*. Gender differences in knee joint cartilage thickness, volume and articular surface areas: assessment with quantitative three-dimensional MR imaging. Skeletal Radiol 2001;30:144–50.
20. Eckstein F, Lemberger B, Gratzke C, Hudelmaier M, Glaser C, Englmeier KH, *et al*. *In vivo* cartilage deformation after different types of activity and its dependence on physical training status. Ann Rheum Dis 2005;64:291–5.
21. Burgkart R, Glaser C, Hyhlik-Durr A, Englmeier KH, Reiser M, Eckstein F. Magnetic resonance imaging-based assessment of cartilage loss in severe osteoarthritis: accuracy, precision, and diagnostic value. Arthritis Rheum 2001;44:2072–7.
22. Eckstein F, Heudorfer L, Faber SC, Burgkart R, Englmeier KH, Reiser M. Long-term and resegmentation precision of quantitative cartilage MR imaging (qMRI). Osteoarthritis Cartilage 2002;10:922–8.
23. Glaser C, Faber S, Eckstein F, Fischer H, Springer V, Heudorfer L, *et al*. Optimization and validation of a rapid high-resolution T1-w 3D FLASH water excitation MRI sequence for the quantitative assessment of articular cartilage volume and thickness. Magn Reson Imaging 2001;19:177–85.
24. Graichen H, von Eisenhart-Rothe R, Vogl T, Englmeier KH, Eckstein F. Quantitative assessment of cartilage status in osteoarthritis by quantitative magnetic resonance imaging: technical validation for use in analysis of cartilage volume and further morphologic parameters. Arthritis Rheum 2004;50:811–6.
25. Eckstein F, Faber S, Muhlbauer R, Hohe J, Englmeier KH, Reiser M, *et al*. Functional adaptation of human joints to mechanical stimuli. Osteoarthritis Cartilage 2002;10:44–50.
26. Stammberger T, Eckstein F, Michaelis M, Englmeier KH, Reiser M. Interobserver reproducibility of quantitative cartilage measurements: comparison of B-spline snakes and manual segmentation. Magn Reson Imaging 1999;17:1033–42.
27. Stammberger T, Eckstein F, Englmeier KH, Reiser M. Determination of 3D cartilage thickness data from MR imaging: computational method and reproducibility in the living. Magn Reson Med 1999;41:529–36.
28. Hohe J, Ateshian G, Reiser M, Englmeier KH, Eckstein F. Surface size, curvature analysis, and assessment of knee joint incongruity with MRI *in vivo*. Magn Reson Med 2002;47:554–61.
29. Eckstein F, Winzheimer M, Hohe J, Englmeier KH, Reiser M. Interindividual variability and correlation among morphological parameters of knee joint cartilage plates: analysis with three-dimensional MR imaging. Osteoarthritis Cartilage 2001;9:101–11.
30. Eckstein F, Muller S, Faber SC, Englmeier KH, Reiser M, Putz R. Side differences of knee joint cartilage volume, thickness, and surface area, and correlation with lower limb dominance—an MRI-based study. Osteoarthritis Cartilage 2002;10:914–21.
31. Bergmann G, Graichen F, Rohlmann A. Hip joint loading during walking and running, measured in two patients. J Biomech 1993;26:969–90.
32. Simon WH. Scale effects in animal joints. I. Articular cartilage thickness and compressive stress. Arthritis Rheum 1970;13:244–56.
33. Anderson JJ, Felson DT. Factors associated with osteoarthritis of the knee in the first national Health and Nutrition Examination Survey (HANES I). Evidence for an association with overweight, race, and physical demands of work. Am J Epidemiol 1988;128:179–89.
34. Jarvholm B, Lewold S, Malchau H, Vingard E. Age, bodyweight, smoking habits and the risk of severe osteoarthritis in the hip and knee in men. Eur J Epidemiol 2005;20:537–42.
35. Ateshian GA, Wang H. A theoretical solution for the frictionless rolling contact of cylindrical biphasic articular cartilage layers. J Biomech 1995;28:1341–55.
36. Muehleman C, Bareither D, Huch K, Cole AA, Kuettner KE. Prevalence of degenerative morphological changes in the joints of the lower extremity. Osteoarthritis Cartilage 1997;5:23–37.
37. Wilson W, van Burken C, van Donkelaar C, Buma P, van Rietbergen B, Huiskes R. Causes of mechanically induced collagen damage in articular cartilage. J Orthop Res 2006;24:220–8.